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Proposal and performance evaluation of a Fiber-To-The-Antenna system for video distribution operating in the S-band

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ABSTRACT

It is well known that fiber-radio schemes merge the high speed of the optical links with the wide-coverage and mobility features of wireless systems. In this regard, we present the performance evaluation of a hybrid fiber-radio communication system for video distribution operating in the S-band. We demonstrate experimentally the generation of a series of microwave passband windows over 0.01–10 GHz range obtained by the interaction of an externally modulated multimode laser diode emitting at 1.55 μm associated to the chromatic dispersion parameter of an optical fiber as well as the length of the optical link. Also, demonstrated experimentally is the transmission of TV-signal coded on the microwave signals located at 2.27 GHz and 4.54 GHz, its propagation over an optical link of 25.24 km, and finally its distribution to multiple users by using an antenna. The originality of this work resides in the fact that the filtered microwave signals used as electrical carriers are function of the distance between the central site and the antenna; therefore it is possible to assign a particular microwave passband for certain services. Experimental results allow us to demonstrate that the Fiber-To-The-Antenna scheme is a promising technique for multiservice distribution.

1. Introduction

Currently, there is an increasing demand for delivering data and video services to a large number of users in optical and wireless access services [1,2]. In this sense, hybrid optical access networks integrating Fiber-To-The-Antenna (FTTA) are promising for future multiservice access networks [3,4]. Hybrid systems have been regarded as a key technique to meet the bandwidth requirements for delivering data and video service to a large number of users in optical and wireless access systems because they show many advantages such as low cost, large bandwidth, high transmission performance, and high mobility [5], and as such, have been widely investigated. By utilizing hybrid systems, radio frequency (RF) signals can be efficiently distributed to densely populated areas or outdoor ranges. FTTA use tower-mounted remote radio units (RRUs) to generate the signal at the top of the tower, near the antenna, with a coaxial jumper cable connecting them. With a short distance to travel over the coax, signal loss is minimal. Under this scheme, the data signal from a central site (CS) can be transmitted via an optical link (high-bandwidth and low signal loss) directly to the RRU in order to be radiated to multiple users as is illustrated in Fig. 1.

On the other hand, inherent features of the microwave photonic filters (MPFs), such as lower losses, broader bandwidth and immunity to electromagnetic interference, make them a very interesting choice compared to conventional electrical filters [6,7]. The factors previously described, together with the increasing demand for multiple communications applications with a great amount of associated information, justify the introduction of MPFs into the access optical networks [8]. Accordingly, the goal of this work is to evaluate an experimental scheme based on a hybrid fiber-radio communication system for video distribution based on a MPF consisting of four passband windows in the frequency range of 0.01–10 GHz. These passband windows can be tailored or adjusted to the function of the free spectral range (FSR) of the optical source, the chromatic dispersion parameter of the optical fiber used, as well as the length of the optical link. In particular, the filtering effect is obtained by the interaction of an externally modulated multimode laser diode (MLD) emitting at 1.5 μm associated to the length of a dispersive optical fiber. The performance evaluation of the MPF is validated by a theoretical analysis as well as by simulation. Results indicate that the MPF is a promising candidate in a hybrid access network. The aim of this work is to experimentally demonstrate the transmission of TV-signal

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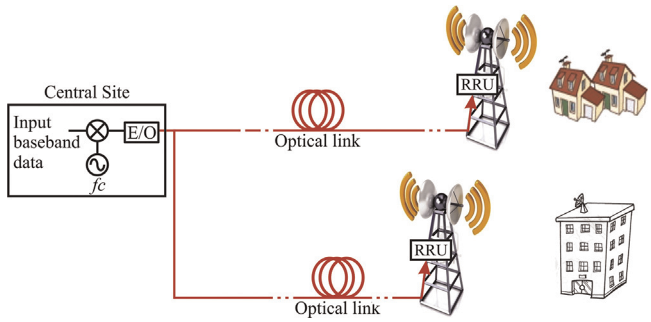

Fig. 1. Hybrid optical access network-FTTA concept.

coded on the microwave signals located at 2.27 GHz and 4.54 GHz and its propagation over a long-haul optical link of 25.24 km; finally at the end of the optical link the TV-signal is wirelessly distributed to multiple users by an antenna. The originality of this work resides in the fact that the filtered microwave signals used as electrical carriers are functions of the distance between the central site and the antenna, and as such, certain services can be assigned to certain microwave passbands. Practical applications for this approach lie in the field of the FTTA access network for distribution of services, like video, voice, and data. The remainder of this paper is prepared as follows. After a brief review of the basic operation of the MPF in Section 2, we devote Section 3 to describing a series of experiments that support the approach here proposed. Finally, conclusions are given in Section 4.

2. Principle

As has been reported in [9,10], the frequency response of the microwave photonic filter (MPF) depicted in Fig. 2 is determined by the real part of the Fourier transform of the optical spectrum of the optical source used. Readers are referred to these references for a detailed description of the principle of operation.

In the following, we indicate the equations that allow us to determine its behavior. In a first step, the central frequency of the nth passband filtered in the frequency response of the MPF can be determined as [9,10]

$$f_n = n\left(\frac{1}{DL\delta_\lambda}\right) \tag{1}$$

where n is a positive integer ($n=1, 2,\ldots$), D is the chromatic dispersion parameter, L is the length of the optical fiber, and δ_λ is the free spectral range (FSR) of the spectrum given in nm. In the second step, the low-pass frequency response of the MPF is determined as

$$f_{lp} = -\frac{2\sqrt{\ln 2}}{\pi DL\Delta\lambda} \tag{2}$$

Finally, the bandwidth of each passband window at -3 dB of the nth passband window is determined by

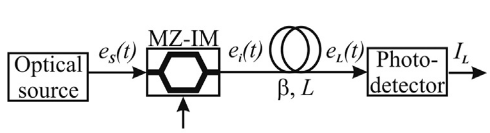

Fig. 2. Basic topology of the microwave photonic filter [9,10].

$$\Delta f_{bp} = 2\left(f_{lp}\right) \tag{3}$$

In summary, the transfer function of the MPF is composed of a low-pass band centered at zero frequency and multiple passband windows that depend on the spectral profile of the optical source, on the chromatic dispersion value of the optical fiber, and on its length.

3. Results

This section is divided into two subsections. First, we describe the simulation and experimental evaluation of the frequency response of the MPF in the frequency range of 0.01–10 GHz. Next, we explain the experimental transmission of TV-signal coded on the microwave signals located at 2.27 GHz and 4.54 GHz, its propagation over an optical link of 25.24 km, as well as its distribution to multiple users by using an antenna.

3.1. Experimental evaluation of the frequency response of the MPF

In this subsection we explain how the filtered microwave passbands are generated considering three parameters. These are as follows. First, the optical characteristics of the MLD at an optical power of 1.5 mW, are $\lambda=1.533$ µm, FWHM$=4.10$ nm, and $\delta_\lambda = 1.1$ nm. Second, a length of $L=25.24$ km of Single-Mode-Standard-Fiber (SM-SF) is considered. Third, according to the manufacturer specifications, the chromatic fiber-dispersion parameter is $D=15.81$ ps/nm km. These parameters are fed to a software recently reported by the authors [11], allowing in this way to compute the microwave bands generated by the effect of filtering. Fig. 3 corresponds to the Graphical User Interface (GUI) of this software. In the following we describe in detail each section of this screen.

a. *Edition block (top left)*:
   In this section the user can supply the parameters that can be associated with the electro-optical modulator as – AM electrical signal, optical fiber, chromatic dispersion value, and the type of optical source (Gaussian or multimode).
   Parameters for the electro-optical modulator as – half wave voltage (V_π) in volts and, initial transmittance phase shift (ϕ_0) in radians.
   Parameters for the AM electrical signal as – amplitude (peak voltage), carrier frequency (in GHz), and baseband signal frequency (in MHz).
   Parameters for the optical fiber as – Length (L) in kilometers, and chromatic dispersion parameter (D) in ps/nm km
   Parameters for the laser source as – search a file containing a real optical spectrum or edit an optical spectrum, providing the central wavelength (λ_0) in nanometers, envelope shape (Gaussian, Lorentzian, $\cos^2$), modes shape (Gaussian, Lorentzian, without modes), spectral width (FWHM, $\Delta\lambda$) in nanometers, free spectral range ($\delta\lambda$) in nanometers.

b. *List of theoretical, simulated and experimental central frequencies (top right)*:
   This section displays a list of theoretical, simulated and experimental values of the resonance frequencies in the frequency response of the microwave photonic filter.

c. *Optical spectrum or transmittance function display (bottom left)*:
   In this window the user can observe either an optical spectrum obtained from an analytical expression (as is the case illustrated here), or an optical spectrum corresponding to a real source which has been previously recorded using an Optical Spectrum Analyzer. The displayed optical spectrum is used for

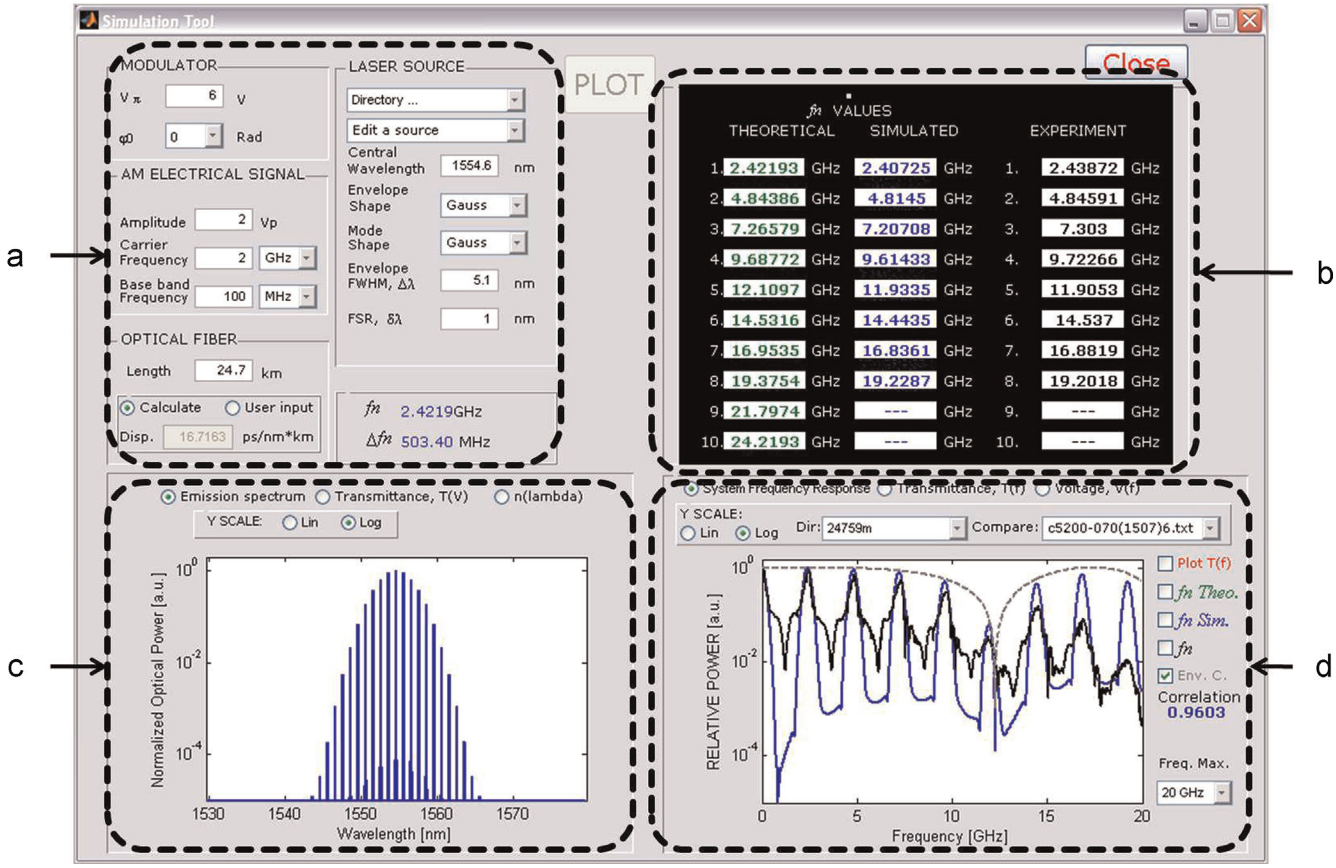

Fig. 3. Graphical User Interface (GUI) of the simulation tool to compute the passband windows.

executing a simulation. Another option available on this window is to display the transmittance function. In both cases the user can select a linear or logarithm scale and, at the same time, select the range to display these results.

d. *Simulation (bottom right)*:

This window displays the system frequency response. The most relevant aspect is that the user can display both simulated and experimental results on the same graph, thus allowing a qualitative comparison between the results. Inclusively, the value of correlation between both results is calculated and displayed. Again, the user can select linear or logarithm scale and, at the same time, select the range to display these results.

Considering the values previously defined, the frequency response of the MPF contains four band passes in the frequency range of 0.01–10 GHz. The use of this software allows graphically and numerically the computing of band pass windows centered at values of f_1=2.27 GHz, f_2=4.55 GHz, f_3=6.83 GHz, and f_4=9.11 GHz. The average bandwidth at −3 dB of each passband window is Δ_{fbp} = 647.90 MHz. These numerical values are in good agreement with the use of Eq. (1). Now, in order to evaluate experimentally the frequency response of the MPF, the setup illustrated in Fig. 4 is assembled.

The light issued by the MLD is injected into the optical isolator (OI) in order to avoid reflections to the source. The use of a temperature-controller allows us to guarantee the stability of the optical parameters to thermal fluctuations. Since the Mach Zehnder-Intensity Modulator (MZ-IM) is polarization-sensitive, a Polarization Controller (PC) is used to maximize the modulator output power. The lightwave is intensity-modulated via the MZ-IM, which is driven by a RF signal supplied by a microwave signal generator in the frequency range of 0.01–10 GHz at an electrical

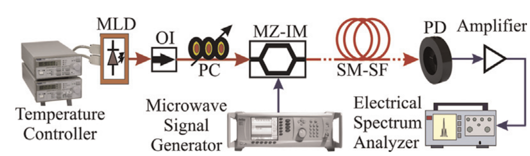

Fig. 4. Experimental setup for filtering microwave signals.

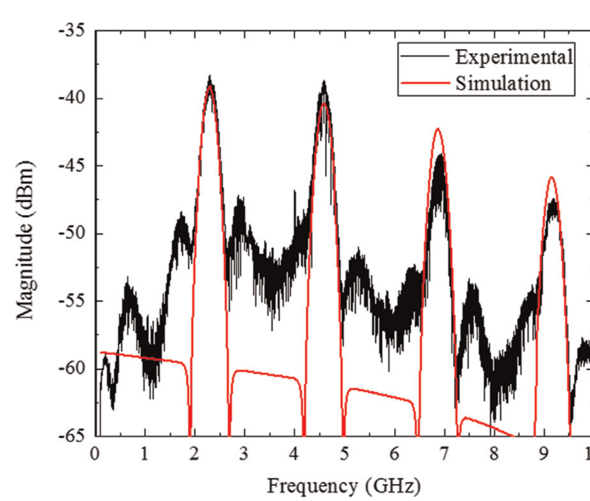

Fig. 5. Experimental and simulated frequency response of the microwave photonic filter.

power of 10 dBm. The intensity-modulated optical signal is injected into a bobbin of SM-SF of length $L=25.24$ km. After a long fiber transmission, the optical signal is received by a Photo-Detector (PD) and its output connected to an electrical stage amplification, and finally launched to the electrical spectrum analyzer in order to measure the frequency response of the MPF. Fig. 5 illustrates the experimental and simulation frequency response where the presence of four well-formed passband windows is clearly appreciable at $f_1=2.27$ GHz, $f_2=4.54$ GHz, $f_3=6.83$ GHz, and $f_4=9.10$ GHz.

Our experimental results agree well with the calculated results based on theory. The average bandwidth of 613.38 MHz associated to the passband windows allows us to guarantee enough bandwidth in case of fluctuations (in the order of nanometers) between mode-spacing. This consideration permits us to assure good stability for the MPF. The small difference between the theoretical and experimental value of f_n is easily determined by means of the relationship

$$\%\text{error},\ f_n = \frac{\left| f_{n,\text{ theoretical}} - f_{n,\text{experimental}} \right|}{f_{n,\text{theoretical}}} \times 100\% \tag{4}$$

In average, the error rate computed was 0.2%. This value is justified by the uncertainty of the real value of the length of the optical fibers used as well as the real value of the chromatic dispersion parameter.

In addition, the use of the MPF allows us to select a specific passband to code the information to be transmitted. Each passband has a bandwidth of approximately 640 MHz and is separated by 1.8 GHz; this feature ensures a crosstalk and interference free transmission. It is well worth highlighting the tunability of the MPF that can be achieved by varying the optical fiber length or adjusting the FSR between the modes of the optical source.

3.2. Experimental transmission and distribution of a TV-signal

The schematic diagram of the proposed hybrid fiber-radio scheme or Fiber-To-The-Antenna for transmission and distribution of a TV-signal is shown in Fig. 6. In the first step, we describe the experiment achieved to demonstrate the use of the passband windows placed at 2.27 GHz as an electrical carrier. At the side of the central site (dotted box on the left) audio and video signal of a DVD player is modulated at the frequency of 67.25 MHz corresponding to the carrier of channel 4 of the National Television System Committee (NTSC) standard. The microwave signal generator provides a signal of 2.27 GHz at an electrical power of 15 dBm that is used as the electrical carrier and demodulated signal.

This electrical signal is divided into two paths through a power divider; path 1 is connected to an omnidirectional antenna in order to radiate the signal that acts as a demodulated signal, and the rest is mixed (mixer 1) with the analog NTSC signal of 67.25 MHz. The resulting mixed electrical signal is amplified and applied to the MZ-IM for modulating the light emitted by the MLD. At the end of the long-haul optical link (dotted box on the right), the signal is injected to the PD, and its electrical output is then amplified and connected to an electrical mixer (mixer 2) in order to suppress the carrier signal. Another omnidirectional antenna allows us to recuperate the microwave signal that plays the role of the demodulated signal, and after an amplification stage, connected to the mixer. The use of a low-pass filter allows us to nullify undesirable frequencies. Finally, by using another power divider, the recovered analog TV-signal is launched to an electrical spectrum analyzer in order to evaluate the quality of the signal that is being radiated by means of a Yagi antenna to two TV-monitors. Fig. 7(a) shows the measured electrical spectrum of the transmitted and recovered TV-signal, obtaining a signal-noise-ratio (SNR) of 46.01 dB and 38.25 dB, respectively. Thus, the signal deteriorates over the transmission by the system 7.7 dB approximately.

In the second step, we demonstrate the use of the second band pass window (4.54 GHz) as an electrical carrier. For this goal, the microwave signal generator is tuned at 4.54 GHz (electrical power of 15 dBm). Again, the signal of 4.54 GHz is mixed with the analog NTSC signal of 67.25 MHz and the resulting signal applied to the MZ-IM for modulating the light of the MLD. At the output of the PD the electrical signal is amplified and connected to the electrical mixer (mixer 2) in order to suppress the carrier signal of 4.54 GHz. After filtering, at the output of the power divider the recovered analog TV-signal is radiated by the Yagi antenna to the TV-monitors and at the same time connected to the electrical spectrum analyzer in order to be analyzed. The graphs illustrated in Fig. 7 (b) correspond to the measured electrical spectrum of the transmitted and recovered TV-signal obtaining a SNR of 46.01 dB and 37.83 dB, respectively. Thereby, the signal deteriorates over the transmission by the system 8.1 dB approximately.

Fig. 8(a) shows a screen of the oscilloscope where upper and lower traces are the time domain waveforms of standard NTSC composite color video signal corresponding to the transmitted and recuperated signals using the passband window of 2.27 GHz. Finally, Fig. 8(b) corresponds to a picture of the screenshot of the TV-monitor showing a scene of the film "Annie" without noticeable degradation. The recovered sound was also very clear.

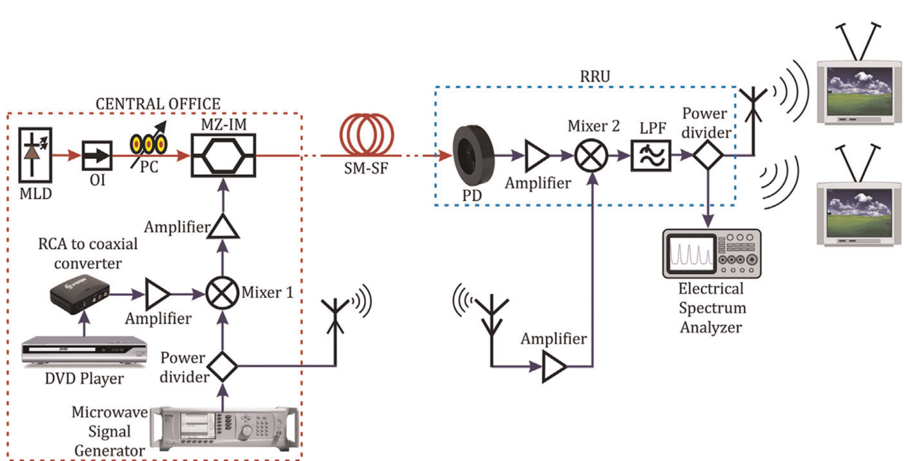

Fig. 6. Schematic setup for TV-signal distribution using a hybrid optical wireless system.

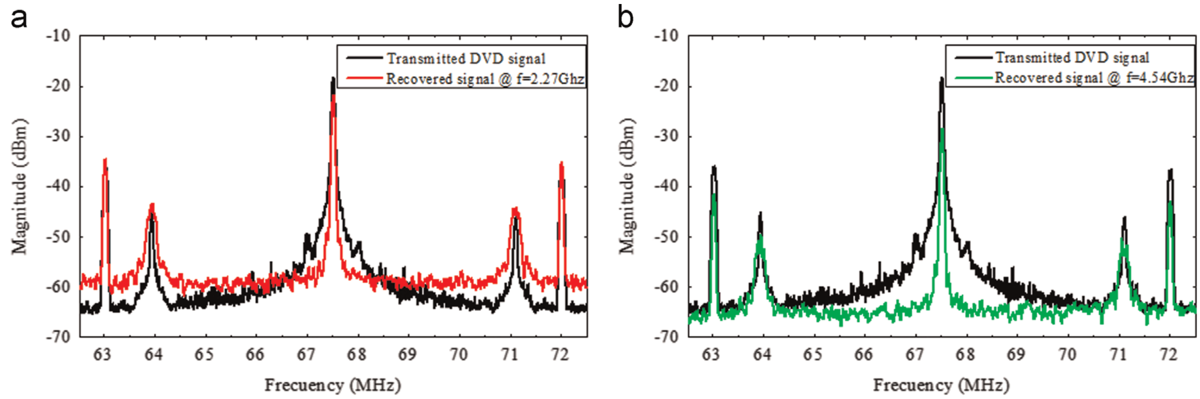

Fig. 7. Electrical spectrums for the transmitted and recovered TV-signal using the passband window of (a) 2.27 GHz and (b) 4.54 GHz.

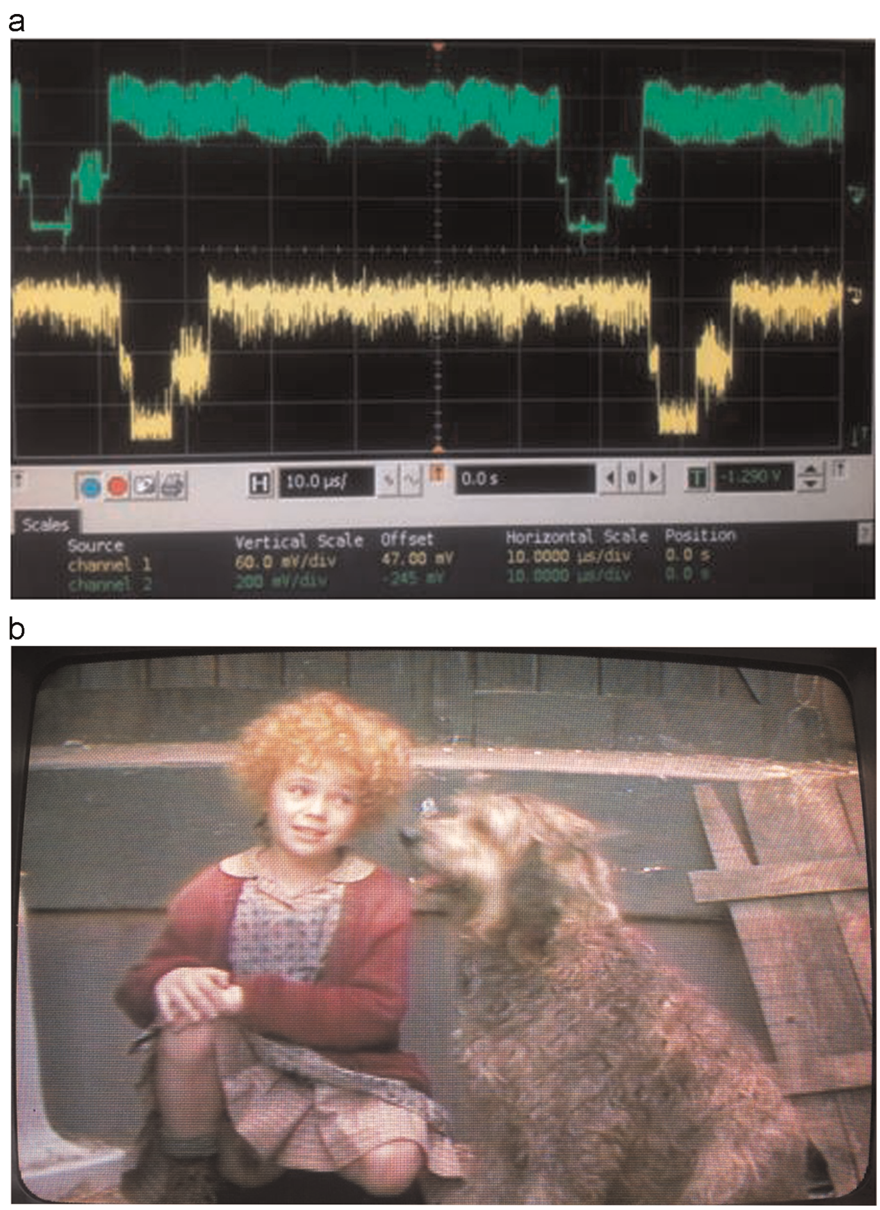

Fig. 8. (a) Time domain waveforms of standard composite color video signal and (b) sample screenshot showing a scene of the film "Annie" recovered by the system.

4. Conclusions

In summary, a hybrid fiber-radio system or Fiber-To-The Antenna scheme represents a key solution for satisfying the current requirements of demand for delivering data and video services to large number of users in optical and wireless access services. A microwave photonic filter was proposed to be used in this FTTA scheme in order to use the filtered microwave passband windows as electrical carries. Because frequency response of the MPF can be tailored to the function of the length of the optical link (distance between the central site and the antenna), it is possible to assign a particular microwave passband for particular services (data, voice, and video). In particular, in this work we have conducted a series of experiments in order to transmit analog NTSC TV-signal coded on microwave passbands located at 2.27 GHz and 4.54 GHz over a long-haul optical link of 25.25 km, and then radiated by an antenna to multiple users. The obtained SNR values are in the acceptable ranges corresponding to optical transmissions [12].

Acknowledgments

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